**Geoengineering and Climate Change: An Assessment using EdGCM**

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## Introduction

The Earth's climate has been warming at an alarming rate in the last few decades and already effecting the environment at a global scale. Global warming is mostly attributed to anthropogenic activities, particularly since the mid twentieth century that led to an unprecedented warming trend of 0.85˚C from 1880 to 2012 (IPCC, 2014). The concentrations of the major greenhouse gases (GHGs) in the atmosphere such as carbon dioxide, methane, and nitrous oxide are on the rise due to the anthropogenic activities in our modern civilizations. The concentrations of the greenhouse gases are on the rise, for example, the concentration of the $CO_2$ in the atmosphere has already reached 400 ppm due to increasing emission from human activities (Figure 1). Other adverse consequences of the warming climate include the warming of the ocean, changing precipitation pattern and intensity, melting of the polar ice caps and glaciers, frequent droughts and heat waves, sea level rise, increase in natural disasters such as tropical cyclones and hurricanes, and so on.

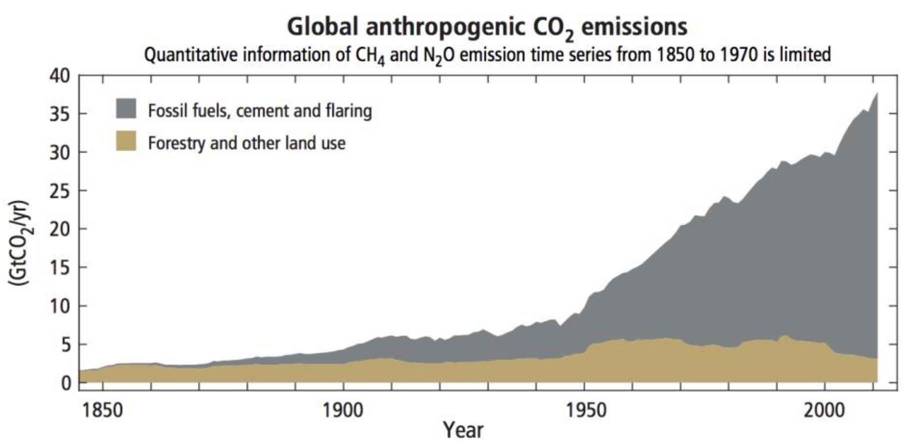


*Figure 1: Annual global $CO_2$ emission from human activities and other land uses (Source: IPCC, 2014)*

To counteract the adverse effects of the warming climate, geoengineering approaches has been proposed with the intention of intervening the Earth's climate at a large scale. There are two broad categories of the geoengineering process: greenhouse gas removal from the atmosphere and the reduction of the incoming solar radiation. The major greenhouse gases such as carbon dioxide can be removed from the atmosphere using biochar, carbon capture and storage, ocean fertilization, bioenergy, enhancing land and ocean carbon sink, afforestation, etc., while the proposed methods for solar radiation reductions are solar radiation management, injecting light-absorbing sulfate particles into the upper atmosphere, increase cloud reflectivity, use of cool roofs, space sunshades, etc. (Preston, 2013; Vaughan and Lenton, 2011). Several studies have found that climate geoengineering is necessary to reduce global warming even if the anthropogenic greenhouse gas emission is halted at the current level or were completely stopped (Cao and Caldeira, 2010; Matthews and Caldeira, 2008; Plattner et al., 2008).

This study aims to analyze the extreme climatic scenario if the greenhouse gases continue to increase in the atmosphere and to investigate the role of climate geoengineering and explore the potentials of reducing global warming. It focuses mainly on the removal of $CO_2$ and $CH_4$ from the atmosphere via geoengineering. However, this study does not specify any particular geoengineering technique. Rather, it assumes a hypothetical scenario of $CO_2$ and $CH_4$ reduction using any geoengineering method to assess its impacts on the climate system. The research questions for this study are (1) What are the effects of increasing concentration of greenhouse gases in the Earth's climate system using RCP8.5 emission scenario? (2) How does the geoengineering approach compare with the RCP8.5 scenario to counteract climate change?

## Model and Methods

This study uses a global climate model (GCM) which is known as EdGCM (Educational Global Climate Model). This model is developed as a joint project between National Aeronautics and Space Administration (NASA) and Goddard Institute for Space Studies (GISS) at Columbia University. The model includes a user-friendly interface that is capable of simulating past and present climate without requiring massive computational power. EdGCM also has a built-in visualization software that allows user to map, plot, and analyze the outputs. It has a horizontal grid size of 8˚ latitude × 10˚ longitude with 9 vertical layers. The model solves the equations of conservation of mass, energy, momentum, and moisture including their transport. It also solves the ideal gas law numerically. It incorporates parameterizations via empirical experiments and physical hypotheses that calculate sub-grid scale processes.

This study utilizes two scenarios for the greenhouse gas emission. First, it replicates one of the trajectories of the concentration of carbon dioxide in the atmosphere as defined by the representative concentration pathways (RCPs) which are included in the Assessment Report 5 (AR5). The RCP 8.5 scenario is adopted in this study that indicates the extreme pathway of the greenhouse gas concentration that result in an increase of radiative forcing by 8.5 $W/m^2$ relative to the pre-industrial value in the year 2100. However, this study only focuses on the concentration of greenhouse gases and does not include other socioeconomic conditions used in AR5 RCP trajectories. Another hypothetical geoengineering scenario is also considered in the study to explore the potentials to combat global warming. In both scenarios, only the greenhouse gas emission rates were varied and the other parameters such as solar luminosity and orbital characteristics were reserved unchanged which allowed to explore the effects of the variations of greenhouse gases concentrations in the Earth's climate.

The rates for the greenhouse gases in the RCP8.5 scenario were chosen as such that the concentrations at the end of the $21^{st}$ century (i.e., year 2100) match with the concentration reported in AR5 in the year 2100. In the geoengineering scenario, the rates were chosen based on the assumption that the concentrations decrease at a rate which is one-half the increasing rate. It was also assumed that the geoengineering method started in the year 2050 and continued until 2100. Table 1 provides the initial values and the trends for the model runs. Period 1 indicates the years 2000 to 2050 and Period 2 indicates the years 2051 to 2100.

*Table 1: Initial values and trends for the RCP8.5 and Geoengineering scenarios forcings*

| | RCP 8.5 | Geoengineering |
|---|---|---|
| Initial CO2/Trends | 368 ppm/ 0.65 %/yr Exponential | 368 ppm/ 0.65%/yr Linear for Period 1<br>-0.33%/yr Linear for Period 2 |
| Initial N2O/Trends | 0.3157 ppm/ 0.0016%/yr Linear | 0.3157 ppm/ no change |
| Initial CH4/Trends | 1.735 ppm/ 0.42 %/yr Exponential | 1.735 ppm/ 0.42 %/yr Linear for Period 1<br>-0.21 %/yr Linear for Period 2 |

| | | |
|---|---|---|
| Initial CFC11 | 0.2646 ppt | 0.2646 ppt |
| Initial CFC12 | 0.5367 ppt | 0.5367 ppt |

These two scenarios were compared to the "Modern_PredictedSST" control run in the EdGCM environment where the greenhouse gases concentrations, solar luminosity, and orbital characteristics are kept constant which result in a steady state climate throughout the 21st century. Thus it is possible to compare the impacts of the RCP8.5 and the geoengineering scenarios with the control run. The model flow chart is given in Figure 1.

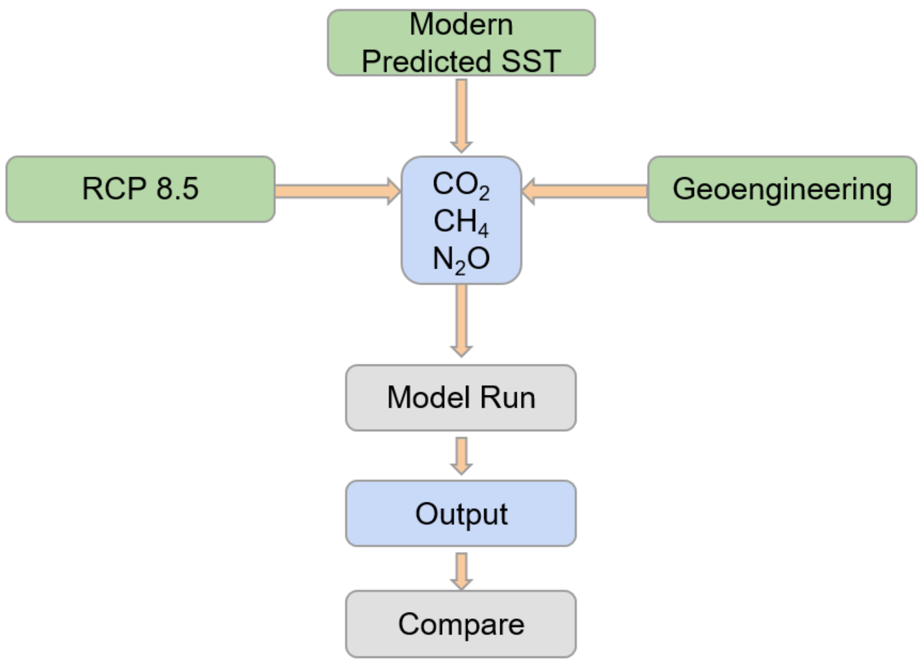


*Figure 2: Flowchart of the methods used in the study*

## Results and Discussion

### *Trends in forcings and global average surface air temperature and snow ice cover*

The observed trends in the greenhouse gases forcings and their impacts on the global surface air temperature and snow and ice cover are shown in Figure 3 and Figure 4, respectively. The forcing trends are obvious, since they were selected for the model input. The RCP 8.5 scenario forcings continuously increase throughout the study period while the geoengineering scenario forcings increase linearly through 2050 and decrease linearly through 2100 except $N_2O$ which was kept constant. The concentrations for the RCP 8.5 scenario in 2100 are 1362.2 ppm, 4.0 ppm, and 0.4789 ppm for $CO_2$, $CH_4$, and $N_2O$, respectively. For the geoengineering scenario, these concentrations in 2100 are 432.6 ppm, 1.93 ppm, and 0.3157 ppm, respectively.

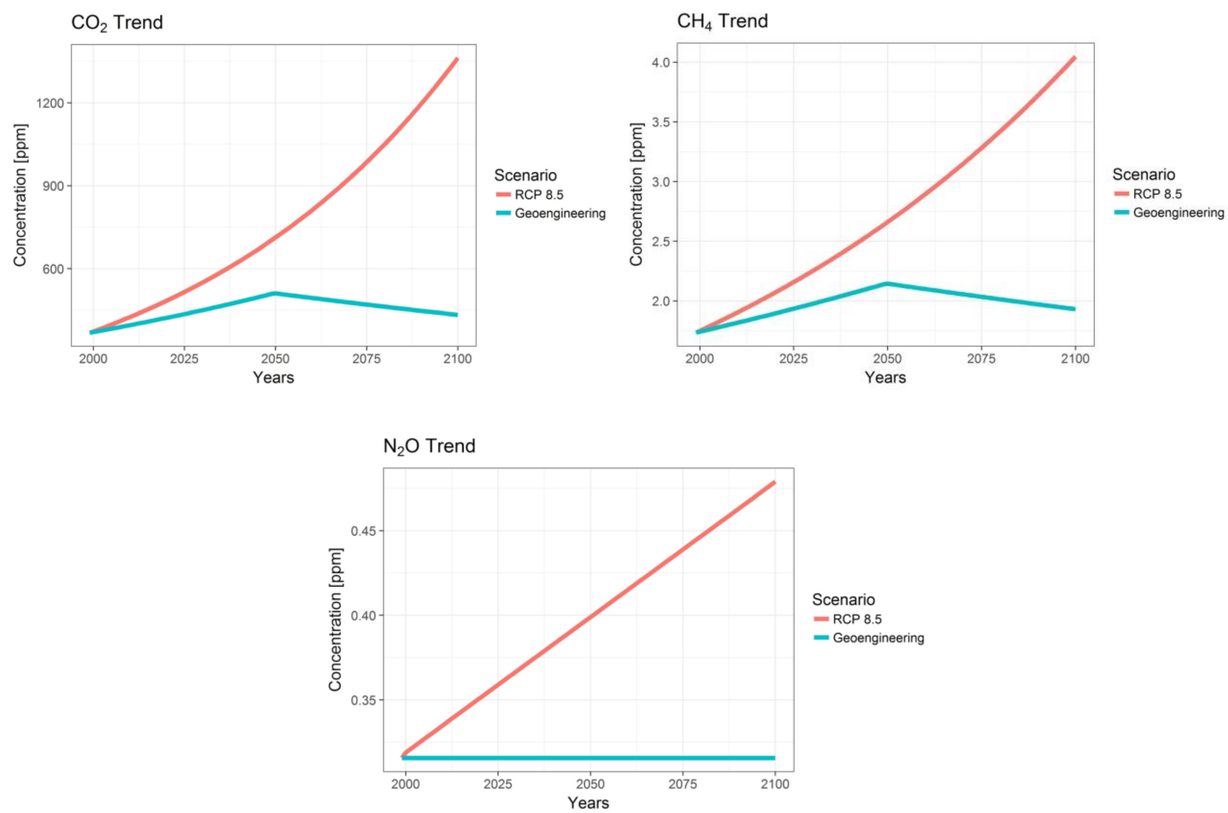


*Figure 3: Forcing trends in RCP8.5 and geoengineering scenarios*

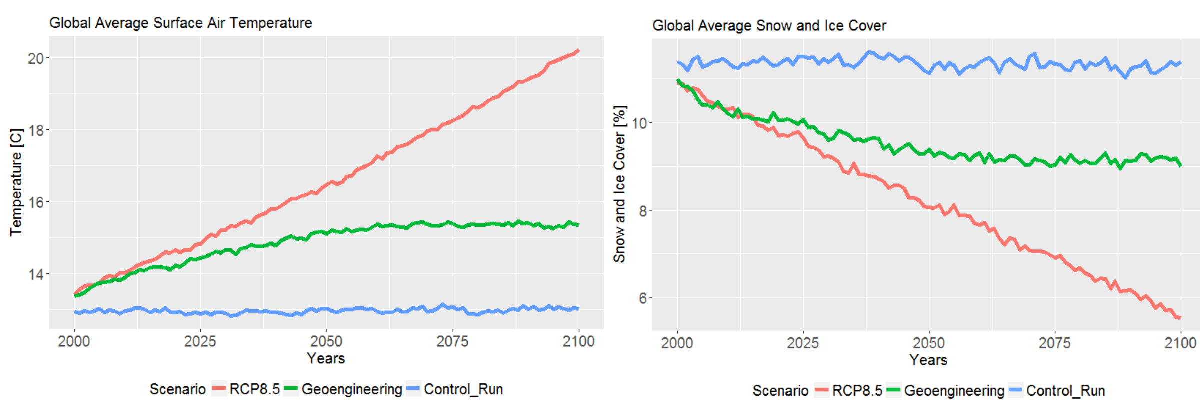


*Figure 4: Comparison of global average surface air temperature and snow and ice cover timeseries*

The trends in global average surface air temperature and snow and ice cover agree with the concentration scenarios. For both variables, the control run scenario show a steady state throughout the 21st century. The global average surface temperature increases from 13.4 C to 20.2 C from 2000 to 2100 in the RCP 8.5 scenario. On the other hand, in the geoengineering scenario, the temperature starts at 13.4 C in 2000 then becomes almost steady around 2060 with a value of 15.3 C. This is a definite effect of the reducing GHGs from the atmosphere. The global snow and ice cover reduces from 10.9% to 5.5% from 2000 to 2100 in the RCP 8.5 scenario due to increasing GHG concentrations. On the other hand, it decreases from 10.9% to 9.2% from 2000 to 2060 and remains almost steady through 2100 due to reduction of GHGs from the atmosphere. In the control run, the global average surface air temperature remains steady at around 13 C and the global average snow ice cover is around 11.4%.

### *Model predictions and comparison between scenarios*

For each scenario, the model outputs for surface air temperature, precipitation, sea surface temperature, and snow and ice cover is used and compared. The projected outputs are shown in Figures 5-8. These figures compare the averages for two time periods, from year 2000 to 2050 (Period 1) and from 2051 to 2100 (Period 2). Comparing these two periods allow us to understand the implications of greenhouse gases in the atmosphere.

The annual global average surface air temperature increases from 14.94 C to 18.33 C from Period 1 to Period 2 in the RCP 8.5 case scenario (Figure 5). This is due to the increasing concentration of the GHGs, particularly $CO_2$ in the atmosphere. In the geoengineering approach, where the GHG emissions are controlled, the annual global average surface air temperature rises from 14.40 C to 15.33 C from Period 1 to Period 2 (Figure 5). The difference plots are shown in Figure 9 where it shows, most of the places on the globe experience a rise of 3-4 C temperature in the RCP8.5 scenario while in the geoengineering scenario the rise is almost uniform across the globe which is below 2 C. In the RCP 8.5 scenario it is seen that the poles experience a greater increase in temperature than the rest of the world. Similar patterns are also seen when the global averages were compared to the control run.

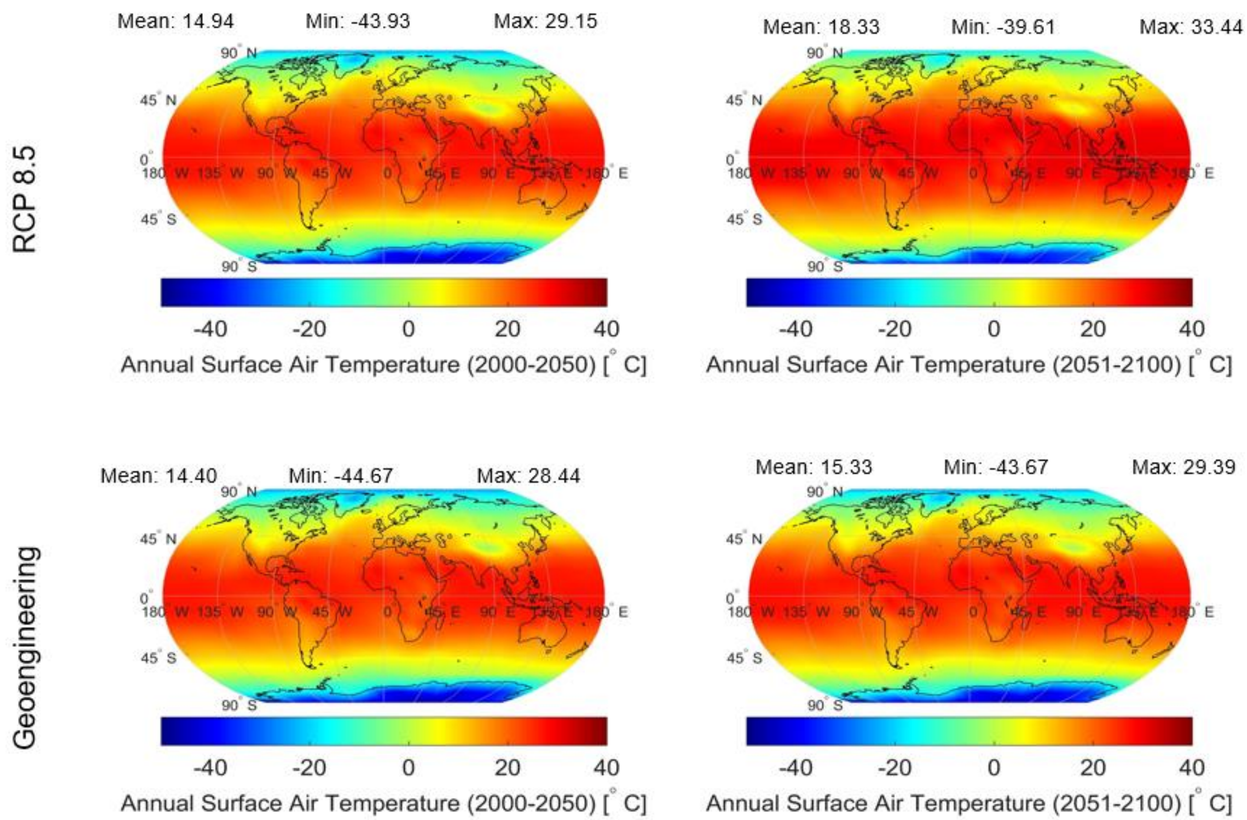


*Figure 5: Average Annual Surface Air Temperature for RCP 8.5 and Geoengineering over Period 1 and 2*

The average annual precipitation for the Periods 1 and 2 for both scenarios are shown in Figure 6 and the differences between the scenarios and with the control run are shown in Figure 10. The mean precipitation increases from 3.18 mm/day to 3.43 mm/day from Period 1 to Period 2 for RCP 8.5 scenario. It increases from 3.15 mm/day to 3.23 mm/day from Period 1 to Period 2 for the geoengineering scenario. The equatorial regions experience higher increase than the other parts of the globe. However, some areas (such as some parts of South America) in RCP 8.5 scenario experience an increase up to 3 mm/day. Some areas in the subtropics experience decrease in precipitation up to 1 mm/day.

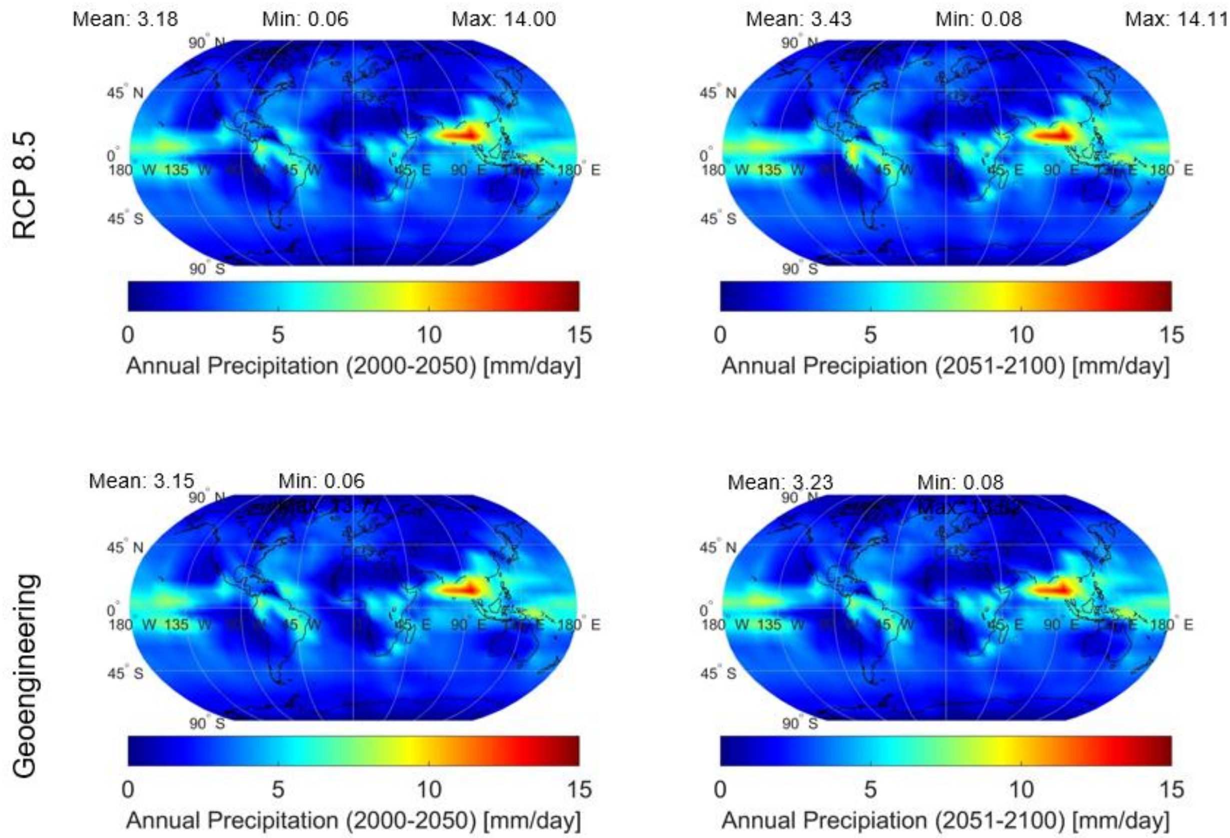


*Figure 6: Average Annual Precipitation for RCP 8.5 and Geoengineering over Period 1 and 2*

The average annual sea surface temperature is shown in Figure 7 and the differences are shown in Figure 11. From Period 1 to Period 2, the increase in annual average sea surface temperature increase from 16.17 C to 18.48 C and 15.83 C to 16.49 C for RCP 8.5 and geoengineering scenarios, respectively. The higher increase in RCP 8.5 scenario is due to the increasing concentration of $CO_2$ in the atmosphere. In RCP 8.5 scenario, the SSTs near the poles experience higher increase compared to the rest of the world. On the other hand, the change in SST is almost uniform across the world ranging from about -1 C to 1 C.

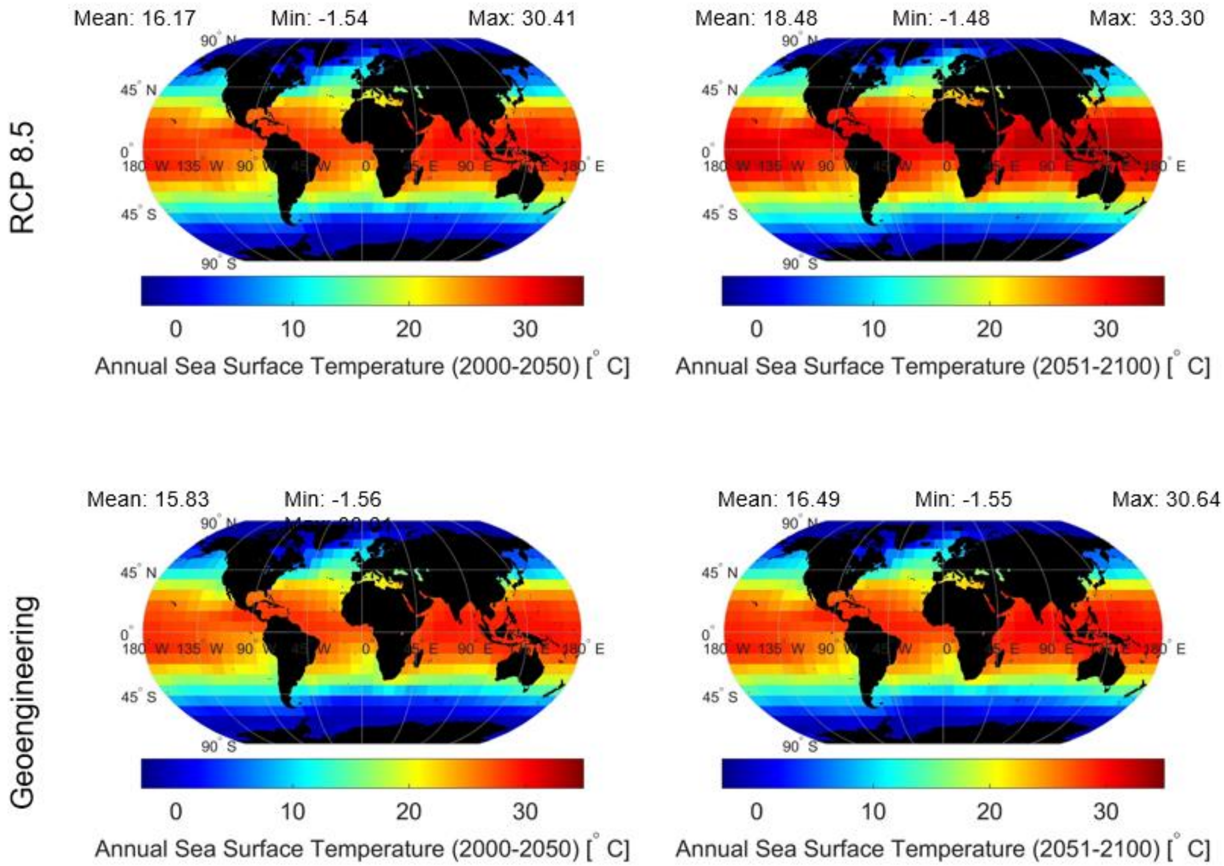


*Figure 7: Average Annual Sea Surface Temperature for RCP 8.5 and Geoengineering over Period 1 and 2*

The snow ice cover percentage is shown in Figure 8 and the differences are shown in Figure 12. The global average snow and ice cover decreases from 10.33 percent to 7.55 percent from Period 1 to Period 2 while it decreases from 10.77 percent to 9.94 percent for the RCP 8.5 and geoengineering scenarios, respectively. In the RCP 8.5 scenario, the snow and ice cover decrease from South America and South Africa. Near the continent Antarctica, the sea ice extent also reduces. The difference plots in Figure 12 show the snow and ice cover decrease up to 60% in the RCP 8.5 scenario. In the geoengineering scenario, the decrease in snow and cover is lower than RCP 8.5 scenario which is up to about 10% in the northern hemisphere and about 25% in the southern hemisphere. When compared to the control run, the decrease in snow and cover is higher in RCP 8.5 scenario. In the northern hemisphere the decrease in snow and ice cover is about 30% while the southern hemisphere experiences higher decrease which is about maximum 60%. The decrease in the geoengineering scenario compared to the control run is about maximum 30% in the northern hemisphere and about maximum of 40% in the southern hemisphere. The reduction in snow and ice cover can be explained by the increase in GHGs in the atmosphere in the RCP 8.5 scenario. The reduction is much lower in the geoengineering scenario which also can be explained by the removal of the GHGs from the atmosphere in the latter half of the 21st century.

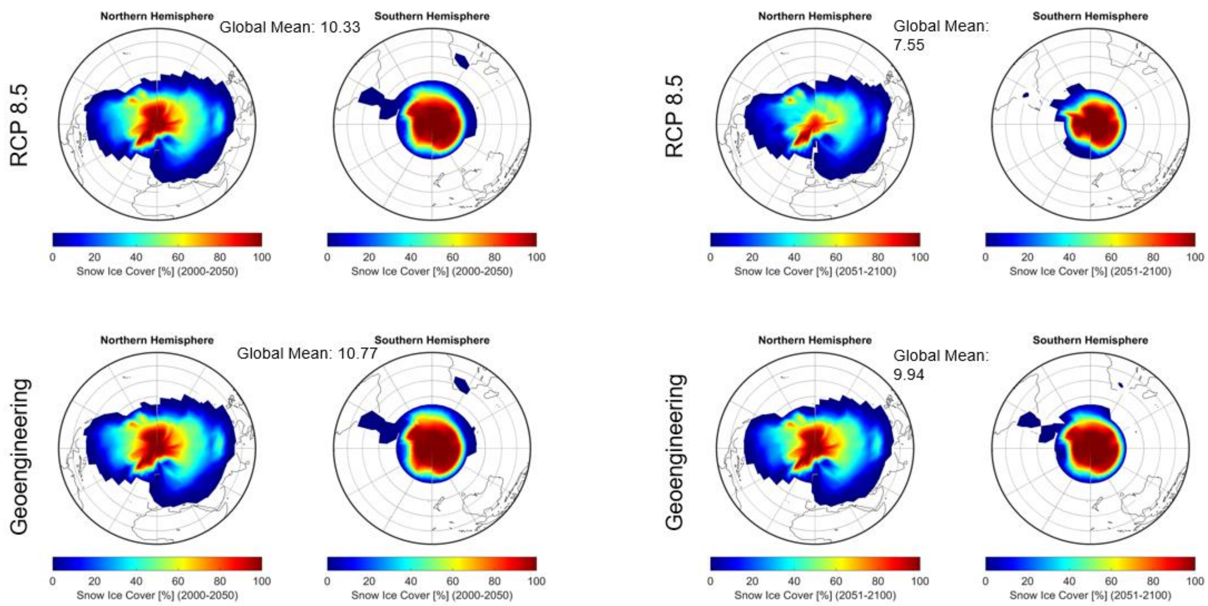


*Figure 8: Average Annual Snow and Ice Cover for RCP 8.5 and Geoengineering over Period 1 and 2*

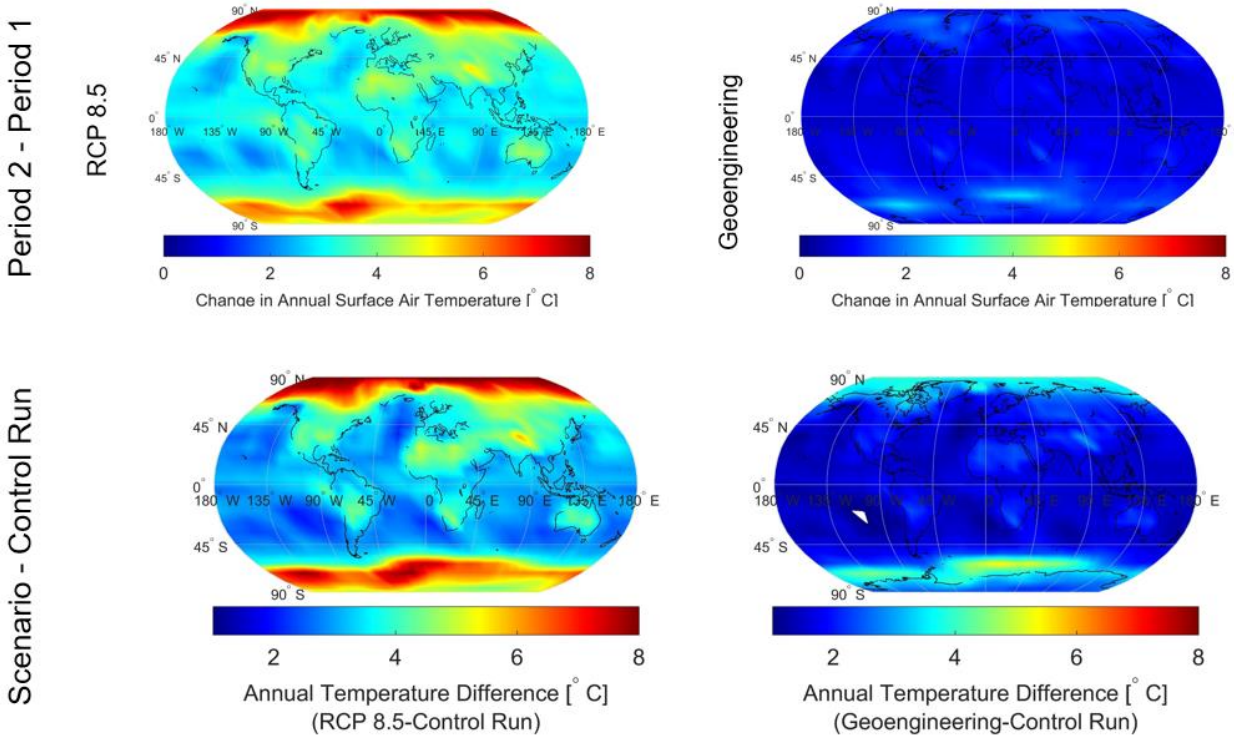


*Figure 9: Average Annual Surface Air Temperature differences for RCP 8.5 and Geoengineering from Period 2 to 1 and with control run for the entire period*

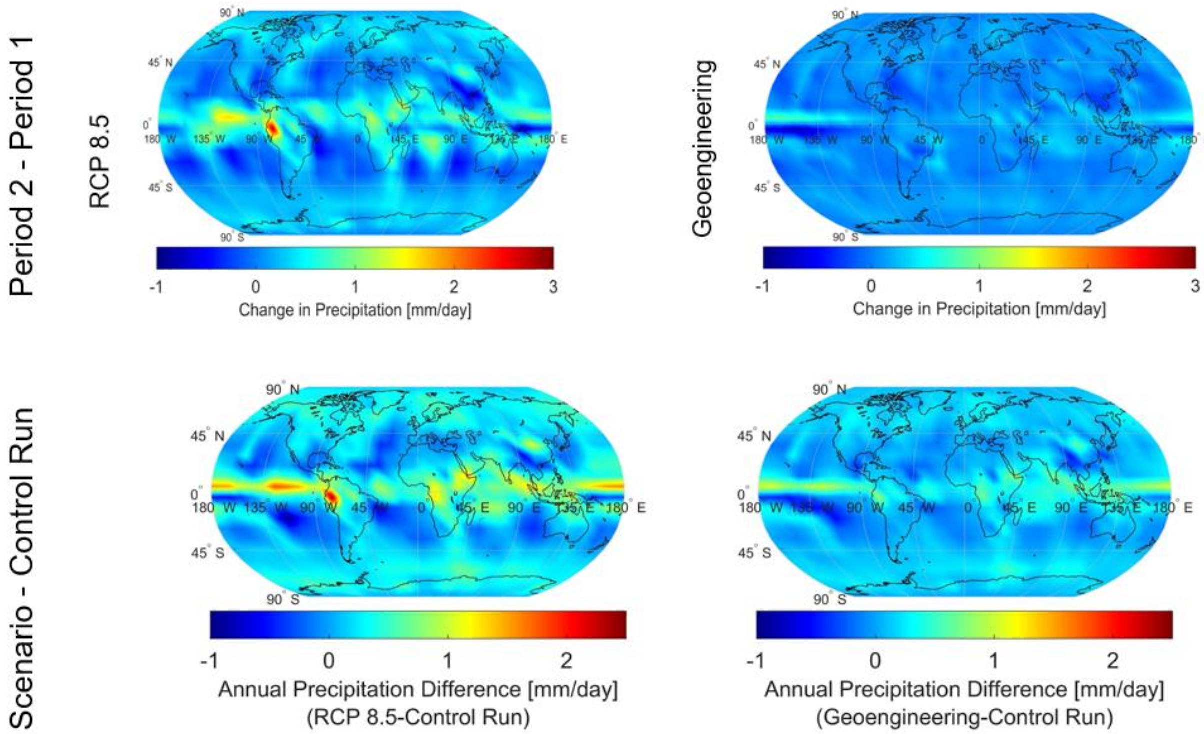


*Figure 10: Average Annual Precipitation differences for RCP 8.5 and Geoengineering from Period 2 to 1 and with control run for the entire period*

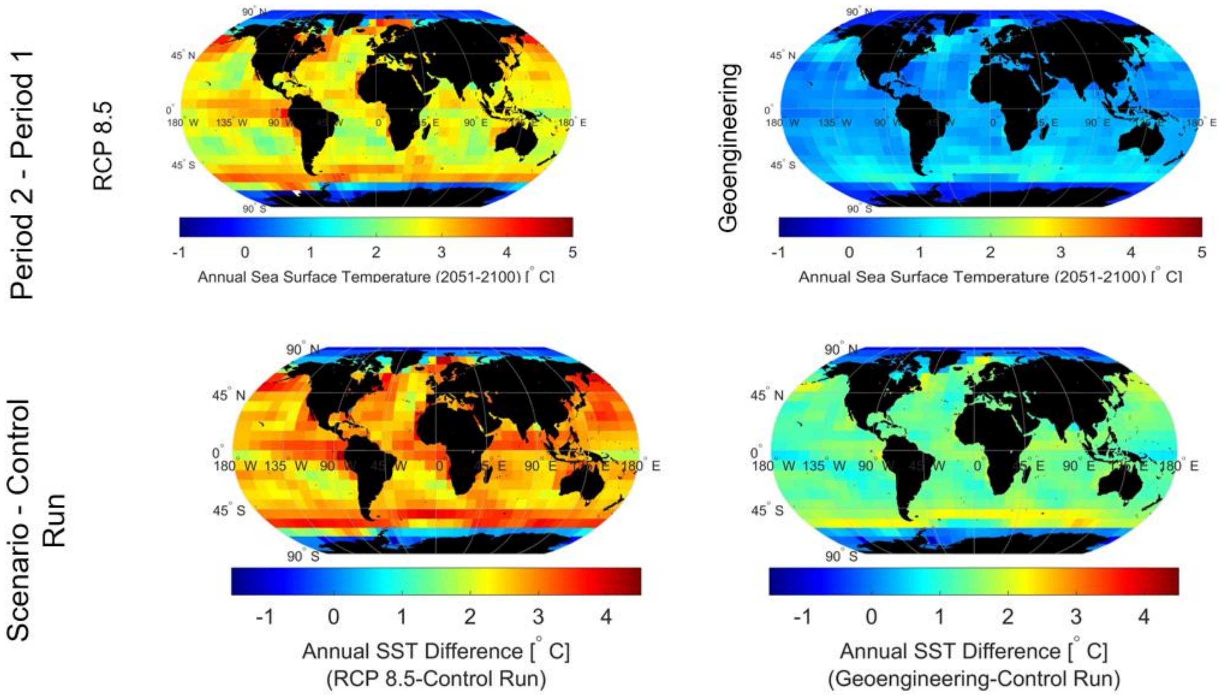


*Figure 11: Fig.9 Average Annual Sea Surface Temperature differences for RCP 8.5 and Geoengineering from Period 2 to 1 and with control run for the entire period*

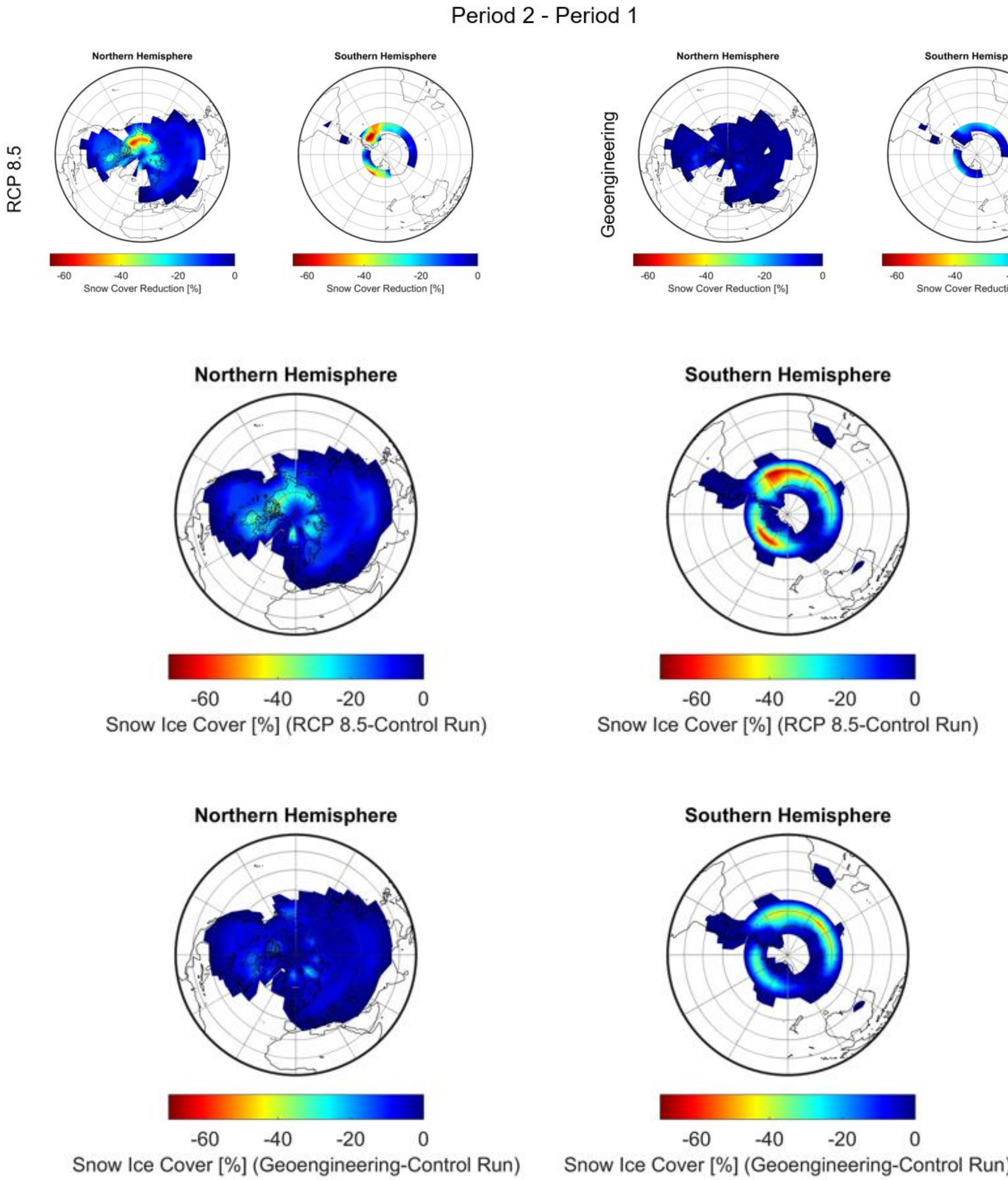


*Figure 12: Average Annual Snow and Ice Cover differences for RCP 8.5 and Geoengineering from Period 2 to 1 (top row) and Average Annual Snow and Ice Cover differences for RCP 8.5 and Geoengineering with control run for the entire period (middle and bottom row)*

## Conclusion

This study investigates the effects of increasing GHGs due to anthropogenic activities in the atmosphere and explore the potentials for the removal of GHGs in an attempt to combat human-induced climate change. The selected climatic variables are surface air temperature, precipitation, SST, and snow and ice cover. Two scenarios of GHG emissions were considered in the study, one of them is the extreme case of GHG in the atmosphere (a replication of GHG emission in the RCP 8.5 scenario from IPCC AR5) and a potential GHG removal scenario using geoengineering approaches. The results show the extreme consequences of the increasing GHG concentration in the atmosphere such as increase in surface air temperature, increase in precipitation intensity, increase in sea surface temperature, and reduction in snow and ice cover. However, using the hypothetical geoengineering scenario, it can be seen that the increase in surface air temperature, precipitation intensity, and sea surface temperature and a decrease in the snow and ice cover are much lower compared to the RCP 8.5 scenario. Thus geoengineering approach show some potentials for reversing the adverse effects of the man-made climate change. Using modeling approaches, the performance of different geoengineering approaches can be assessed and it will be helpful for the policy maker to implement these approaches to achieve climate goals (e.g., Paris Climate Agreement). However, the study has some limitations. For example, the RCP 8.5 scenario that is used in this study only considers the GHG emission trends and does not consider any socioeconomic factors unlike the actual RCP scenarios described in the IPCC AR5. This study shows a global assessment of the climate scenarios using a coarse resolution of the model which is not suitable for the assessment of small-scale studies. Another important limitation of the study pertaining to the model uncertainty. Global climate projections are performed using multi-model ensembles to have a better confidences in the projections. This study uses only one model which may limit our understandings of the future projections. This study can only be considered as an initial assessment for the geoengineering approaches to limit the adverse effects of climate change.

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